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Optimum Fiber Profile for Ultrashort Pulse Formation by Higher-Order Soliton Compression

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Abstract— **Linear dispersion decreasing fiber (LDDF) profiles has been found nearly optimum in regards to the pulse width (63fs) of the compressed pulse. Based on ultrashort soliton compression a comparative study has been carried out among dispersion compensating fiber (DCF), fiber Bragg grating (FBG) and LDDF. Considering higher order effects compression of higher-order solitons, produces high-quality compressed pulses in femtosecond regime. Nonlinear Schrödinger equation (NLSE) has been solved using split-step Fourier (SSF) method for numerical analysis of ultrashort soliton propagation and compression.**

Keywords—Linear dispersion decreasing fiber, intrapulse Raman scattering, optical soliton

I. Introduction

For a few decades soliton pulse has become a subject of tremendous investigation as it offers the dynamic balance between self-phase modulation (SPM) and group-velocity dispersion (GVD). Extreme and single-cycle nonlinear optics, light-matter interactions, attosecond physics, higher-order harmonic generation, femtosecond laser ablation etc. are the extensive applications of ultrashort optical pulses with soliton nature. In recent years femtosecond pulse is tremendously used in applications like ultra-speed communications [1] refractive surgery [2], ear surgery [3] and cardiovascular surgery [4]. Again ultrashort soliton has become prominent in tissue removal for cancer cell treatment [5, 6]. To get this ultrashort pulse, compression is one of the techniques [7-10]. DCF based soliton compression was previously studied [11]. Compression using FBG was also observed [12, 13]. As a compressor DDF is of great interest [14, 15] also.

Although soliton of width 115fs [15] and 100fs [16] has been obtained using compression technique in DDF, however, the impact of the higher-order effects upon such pulse are not considered in those studies. At the same time most works use long length of DDF. In our study, higher-order effects like third-order dispersion (TOD) as higher-order dispersive effects and self-steepening (SS) and intrapulse Raman scattering (IRS) as higher-order nonlinear effects have been taken into consideration. The pulse width has been calculated as 63fs after compression in our proposed LDDF of 2.05m length. In this paper, comparative study among different fibers (DCF, LDDF and FBG) has been carried out for ultrashort optical soliton compression using fundamental and higher order soliton up to 5th order. Among these three fibers, DDF with linear decreasing dispersion profile has been proposed as the best soliton compressor whereas the compressed pulse width has been demonstrated about 63fs and spatially 523.5pm. For numerical analysis, Nonlinear Schrödinger equation (NLSE) has been solved using split-step Fourier (SSF) method.

In this paper considering higher-order linear and nonlinear effects we have analyzed NLSE governed by which ultrashort soliton propagates. Section 2 describes the basic physics of ultrashort soliton propagation. Section 3 comprises LDDF based higher-order soliton compression up to 5th order and a comparison based on soliton compression among LDDF, DCF and FBG.

II. Ultrashort Soliton Dynamics

Ultrashort optical pulse (pulse width ≤1ps) through a single-mode fiber can be described by the generalized NLSE considering higher-order nonlinear and dispersive effects as [17]

$$\frac{\partial E}{\partial z}+\alpha\frac{E}{2}+\beta_2\frac{i}{2}\frac{\partial^2 E}{\partial T^2}-\beta_3\frac{1}{6}\frac{\partial^3 E}{\partial T^3}=i\gamma\left(|E|^2E+i\frac{1}{\omega_0}\frac{\partial}{\partial T}|E|^2E-T_RE\frac{\partial |E|^2}{\partial T}\right). \quad (1)$$

Here E is the complex envelop of the optical pulse, z is propagated distance by the pulse and T is the time, α stands for the fiber loss coefficient, β_2 and β_3 are the second-order and third-order dispersion respectively. γ is the nonlinearity coefficient, T_R stands as time related to the slope of the Raman gain [17], the term with the factor $1/\omega_0$ is related to the self-steepening effect [17]. Normalized amplitude U of the pulse can be written as

$$E(z,\tau)=P_0\sqrt{\exp(-0.5\alpha z)}U(z,\tau). \quad (2)$$

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Here P_0 denotes the peak power of the incident pulse. The exponential factor in (2) accounts for fiber loss. Hence the (1) takes the form

$$\frac{\partial U}{\partial z}+\frac{i\beta_2}{2L_D}\frac{\partial^2 U}{\partial \tau^2}-\frac{\beta_3}{6L'_D}\frac{\partial^3 U}{\partial\tau^3}=\frac{ie^{-\alpha Z}}{L_{NL}}\left(|U|^2U+is\frac{\partial}{\partial\tau}|U|^2U-\tau_R U\frac{\partial|U|^2}{\partial\tau}\right) \tag{3}$$

Where L_D, L'_D and L_{NL} are the second-order dispersive length, third-order dispersive length and nonlinear length respectively defined as

$$L'_D=\frac{T_0^3}{|\beta_3|},L_{NL}=\frac{1}{\gamma P_0},L_D=\frac{T_0^2}{|\beta_2|}. \tag{4}$$

The parameters s and τ_R govern the effects of self-steepening and intrapulse Raman scattering respectively, and are given as

$$s=\frac{\lambda}{2\pi cT_0},\tau_R=\frac{T_R}{T_0}. \tag{5}$$

Where T_0 is the input pulse width. Both of these effects must be considered for ultrashort pulses (T_0 <1 ps). In terms of normalized amplitude U with normalized distance Z and normalized time τ the (3) can be written as

$$\frac{\partial U}{\partial Z}+\frac{i}{2}\frac{\partial^2U}{\partial\tau^2}-\frac{i}{6}\frac{\partial^3U}{\partial\tau^3}=iN^2e^{-\alpha z}\left(|U|^2U+s\frac{i}{\omega_0}\frac{\partial}{\partial\tau}|U|^2U-\tau_RU\frac{\partial|U|^2}{\partial\tau}\right) \tag{6}$$

Here $$Z=\frac{z}{L_D},U=\frac{A}{\sqrt{P_0}},\tau=\frac{T}{T_0}. \tag{7}$$

For soliton pulse, T_0 is as follows

$$T_0=\frac{T_{FWHM}}{1.763}. \tag{8}$$

Parameter N is the soliton order that provides the measure of the strength of the nonlinear response compared to the fiber dispersion, and is defined as

$$N^2=\frac{L_D}{L_{NL}}=\frac{\gamma P_0T_0^2}{|\beta_2|}. \tag{9}$$

We have observed compression of ultrashort fundamental and higher-order soliton and explored our analysis with return to zero hyperbolic secant pulse of 50% duty cycle. (3) has been solved using SSF method to simulate the compression characteristics of soliton.

III. Higher-Order Soliton Dynamics in LDDF, DCF and FBG

Compression of higher-order soliton has been observed in LDDF, DCF and FBG. At first we have observed the temporal and spectral evolution of compressed soliton in an LDDF with following dispersion profile [18]:

$$\beta_{2n}=\frac{\beta_{2P}}{L\beta}(L\beta+z-z\beta) \tag{10}$$

Where β_{2n}, β_{2p} are the changing group velocity dispersion (GVD) and starting GVD respectively. Here $\beta = \beta_{2p}/\beta_{2L}$, β_{2L} = final GVD and L is the total fiber length. Using LDDF the compression of second order soliton has been shown in Fig. 1(a) with parameters used as T_{FWHM}=500fs, P_0=100W, β_{2p} =−10 ps^2 /km, β_{2L} =−1 ps^2/km, β_3 = 0.029 ps^3/km, γ = 5, s = 0.29, and τ_R = 0.02, N=2. What we have observed is that expansion happened within first 10m of LDDF and then compression occurs in rest 15m. The pulse turns its shape from 500fs to 800fs for first 10m and 800fs to 340fs after compression and propagation within next 15m through LDDF. Fig. 1(b) shows second-order soliton pulse compression as well as reduction in FWHM of pulse width with respect to fiber length in DCF. The fiber shows compression and expansion alternatively. Finally a 500fs input pulse has been compressed up to 480fs by DCF of 2m length. Fig. 1(c) shows second order soliton compression using FBG with fiber parameters of TABLE I, where expansion has observed beyond 3ps and then compression happened up to 2.5ps.

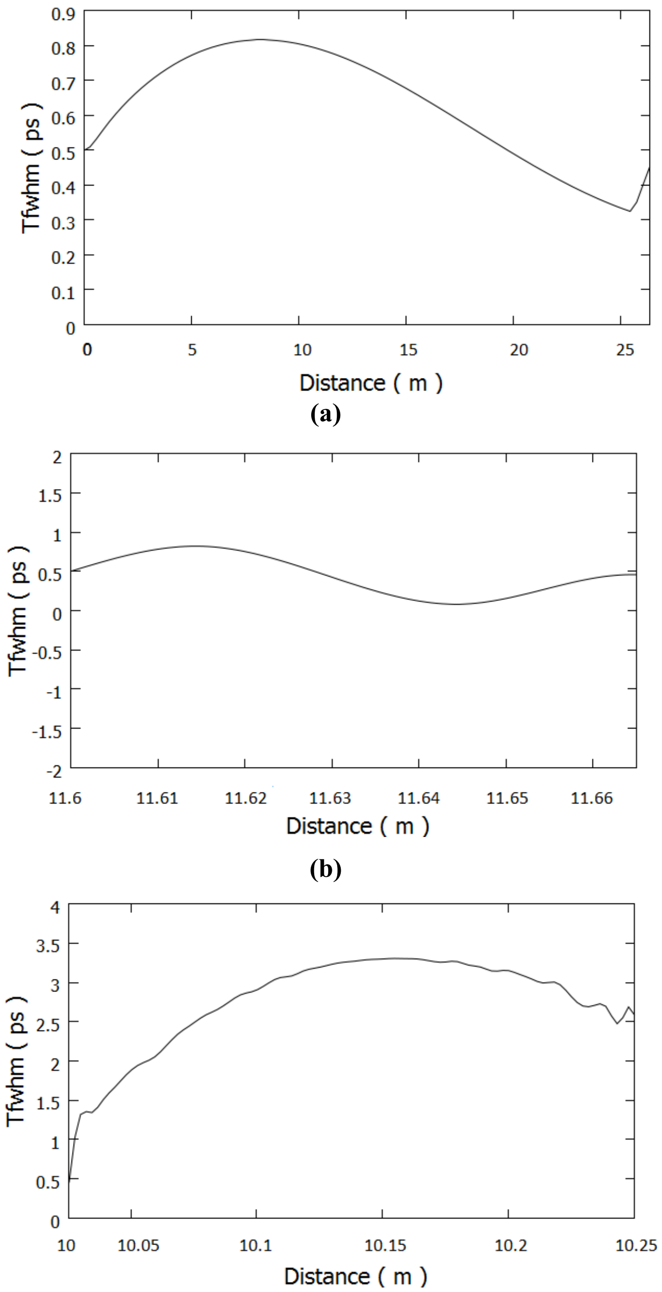
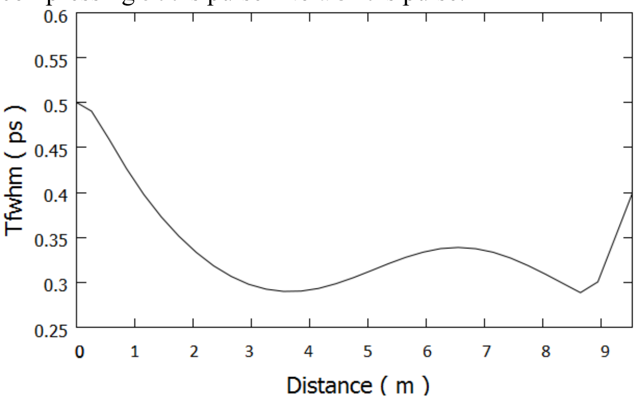
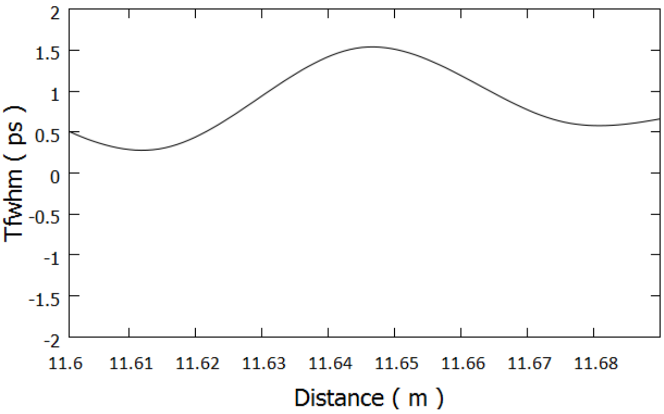


Fig. 1: Pulse width (FWHM) vs. distance curve for second - order soliton in (a) LDDF, (b) DCF and (c) FBG.

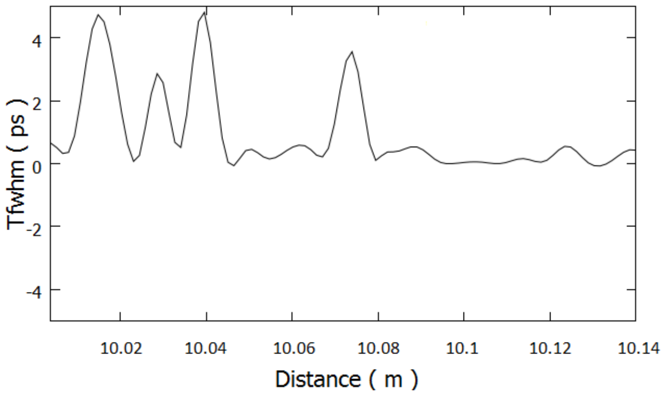
In comparison among LDDF, DCF and FBG for second order soliton compression, LDDF has performed best by compressing 500fs pulse into a 340fs pulse.



(a)



(b)

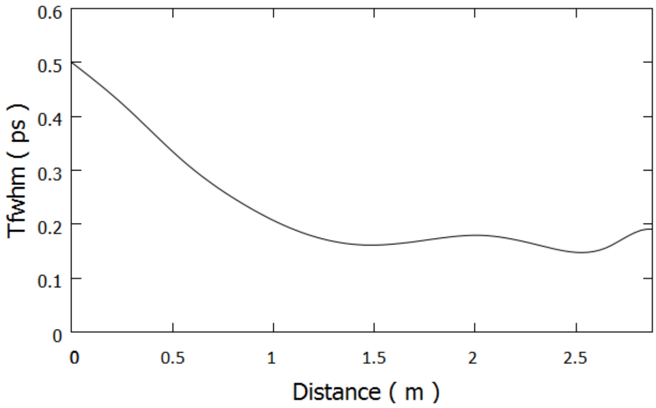


(c)

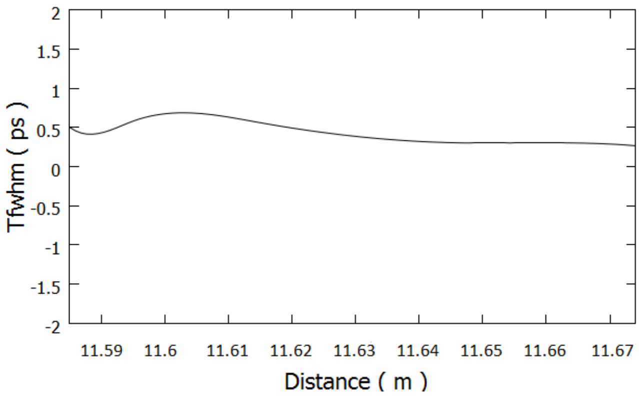
Fig. 2: Pulse width (FWHM) vs. distance curve for third - order soliton in (a) LDDF, (b) DCF and (c) FBG.

Fig. 2(a), 2(b) and 2(c) explore the third order soliton compression in LDDF, DCF and FBG respectively. A smooth curve has observed in LDDF that indicates compression of third order soliton into 300fs shown in Fig. 2(a). DCF based compression can be seen from Fig. 2(b) and an alternative compression and expansion has been observed. Finally a 350fs pulse has been obtained in DCF. FBG based compression has shown in Fig. 2(c). In comparison among LDDF, DCF and FBG for third order soliton compression, LDDF has performed best by compressing 500fs pulse into a 300fs pulse.

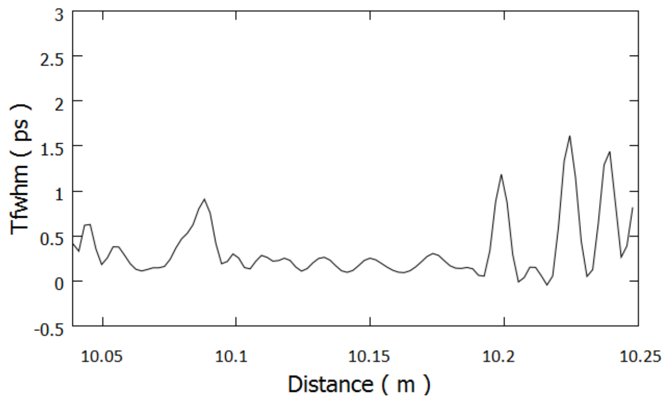
Let us divert our concentration for newer outcome with fourth order sub-picosecond soliton compression experienced in Fig. 3(a), (b) and (c). We have found a very good compression of 500fs pulse into 150fs in LDDF shown in Fig. 3(a). In DCF and FBG with same pulse and parameter we have got nothing but the figure as Fig. 3(b) and Fig. 3(c) respectively. Although the best result has been found above all of the analysis in Fig. 4(a), which shows the compression of ultrashort fifth order optical soliton in LDDF, but it was not so



(a)



(b)



(c)

Fig. 3: Pulse width (FWHM) vs. distance curve for fourth - order soliton in (a) LDDF, (b) DCF and (c) FBG.

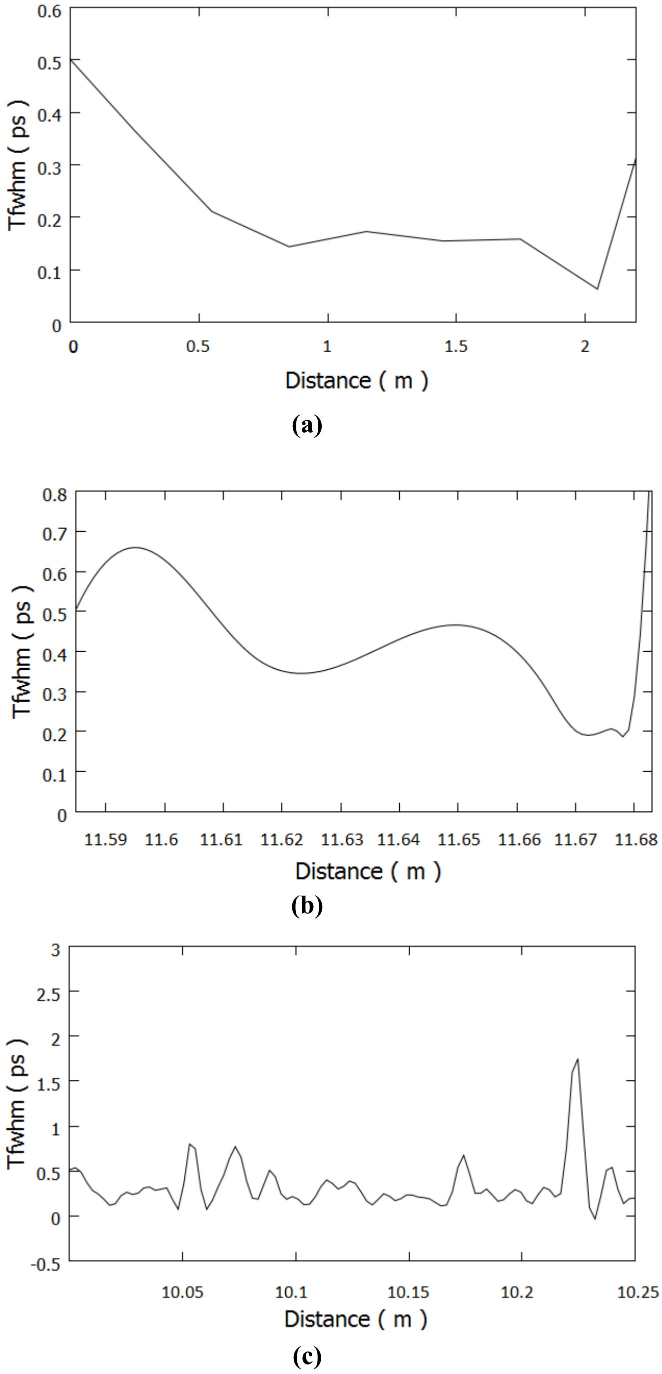


Fig. 4: Pulse width (FWHM) vs. distance curve for fifth - order soliton in (a) LDDF, (b) DCF and (c) FBG.

smooth. The result gives us a compression up to 63fs for fiber length of 2.05m. Beyond this fiber length pulse expansion happens which is clear from Fig. 4(a). This is because as the fiber length increases nonlinear effects dominate the linear effects. Fig. 4(b) and Fig. 4(c) show the result for compression of ultrashort fifth order optical soliton in DCF and FBG as well.

All the data for ultrashort soliton compression in DCF, FBG and LDDF are as follows:

TABLE I PULSE WIDTH AFTER COMPRESSION AND SPATIAL SOLITON DIMENSION FOR 500FS INPUT PULSE

Soliton order	Pulse width (post-comp.) in DCF	Pulse width (post-comp.) in FBG	Pulse width (post-comp.) in LDDF	Spatial dimension of soliton in LDDF
2nd	480fs	Expansion (2.5ps)	340fs	2.72nm
3rd	350fs	300fs	300fs	2.408nm
4th	250fs	400fs	150fs	1.2nm
5th	200fs	200fs	63fs	523.5pm

From all of the above comparison and outcomes for ultrashort optical soliton compression of higher-order soliton up to fifth order we can say, it is obvious that DCF and FBG could not perform a good compression whereas LDDF has performed compression with excellence which has been clearly showed in TABLE I.

IV. CONCLUSION

Considering higher order dispersive effects i.e. TOD and higher order nonlinear effects i.e. SS and IRS the compression of ultrashort optical soliton in DCF, LDDF and FBG has been investigated. Based on ultrashort soliton compression a comparative study has also been explored among dispersion compensating fiber (DCF), fiber Bragg grating (FBG) and LDDF. Finally LDDF of 2.05m length has been proposed for higher-order ultrashort soliton compression for formation of spatial soliton in nm-pm range. We have obtained numerically ultrashort soliton of 63fs after compression. The spatial dimension has been found as 523.5pm.

REFERENCES

[1] S. M. Salimullah and M. Faisal, "Ultrashort soliton propagation in multi-clad optical fibers with per channel data rate of 1Tb/s," in *Telecommunications and Photonics (ICTP), 2015 IEEE International Conference on*, 2015, pp. 1-5.

[2] S. I. Mian and R. M. Shtein, "Femtosecond laser-assisted corneal surgery," *Current opinion in ophthalmology,* vol. 18, pp. 295-299, 2007.

[3] B. Schwab, D. Hagner, W. Müller, H. Lubatschowski, T. Lenarz, and R. Heermann, "Bone ablation using ultrashort laser pulses. A new technique for middle ear surgery," *Laryngo-rhino-otologie,* vol. 83, pp. 219-225, 2004.

[4] H. Lubatschowski, A. Heisterkamp, F. Will, J. Serbin, T. Bauer, C. Fallnich, *et al.*, "Ultrafast laser pulses for medical applications," in *Proc. SPIE*, 2002, pp. 38-49.

[5] I. Amiri, A. Nikoukar, J. Ali, and P. Yupapin, "Ultra-short of pico and femtosecond soliton laser pulse using microring resonator for cancer cells treatment," *Quantum Matter,* vol. 1, pp. 159-165, 2012.

[6] M. Jalil, J. Phelawan, M. Aziz, T. Saktioto, C. Ong, and P. P. Yupapin, "Acne vulgarism treatment using ultra-short laser pulse generated by micro-and nano-ring resonator system," *Artificial cells, nanomedicine, and biotechnology,* vol. 41, pp. 92-97, 2013.

[7] P. Reeves-Hall and J. Taylor, "Wavelength and duration tunable subpicosecond source using adiabatic Raman compression," in *Lasers and Electro-Optics, 2001. CLEO'01. Technical Digest. Summaries of papers presented at the Conference on*, 2001, pp. 228-229.

[8] T. Murphy, "10-GHz 1.3-ps pulse generation using chirped soliton compression in a Raman gain medium," *IEEE Photonics Technology Letters,* vol. 14, pp. 1424-1426, 2002.

[9] S. M. Salimullah and M. Faisal, "Femtosecond Soliton Formation by Higher-Order Soliton Compression in Linear Dispersion Decreasing Fiber," in *Proceedings of 20th Microoptics Conference (MOC'15)*, Fukuoka, Japan., 2015, pp. paper no. H-11.

[10] S. M. Salimullah, "Analysis of higher-order soliton compression for formation of ultra-short pulses," 2015.

[11] C.-C. Chang, A. Vengsarkar, D. Peckham, and A. Weiner, "Broadband fiber dispersion compensation for sub-100-fs pulses with a compression ratio of 300," *Optics letters,* vol. 21, pp. 1141-1143, 1996.

[12] Q. Li, P. Wai, K. Senthilnathan, and K. Nakkeeran, "Modeling self-similar optical pulse compression in nonlinear fiber Bragg grating using coupled-mode equations," *Journal of Lightwave Technology,* vol. 29, pp. 1293-1305, 2011.

[13] Q. Li, K. Senthilnathan, K. Nakkeeran, and P. Wai, "Nearly chirp- and pedestal-free pulse compression in nonlinear fiber Bragg gratings," *JOSA B,* vol. 26, pp. 432-443, 2009.

[14] J. H. Lee, T. Kogure, and D. J. Richardson, "Wavelength tunable 10-GHz 3-ps pulse source using a dispersion decreasing fiber-based nonlinear optical loop mirror," *IEEE Journal of selected topics in quantum electronics,* vol. 10, pp. 181-185, 2004.

[15] S. V. Chernikov, D. Richardson, D. Payne, and E. Dianov, "Soliton pulse compression in dispersion-decreasing fiber," *Optics letters,* vol. 18, pp. 476-478, 1993.

[16] P. Wai and W.-h. Cao, "Ultrashort soliton generation through higher-order soliton compression in a nonlinear optical loop mirror constructed from dispersion-decreasing fiber," *JOSA B,* vol. 20, pp. 1346-1355, 2003.

[17] G. Agrawal, *Applications of nonlinear fiber optics*: Academic press, 2001.

[18] D. Chao-Qing and C. Jun-Lang, "Ultrashort optical solitons in the dispersion-decreasing fibers," *Chinese Physics B,* vol. 21, p. 080507, 2012.